Volumetric Bit-Wise Optical Data Storage for Space Applications

Tom D. Milster

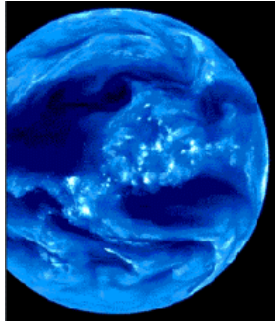Optical Sciences Center

University of Arizona

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Motivation

- On-board processing systems for Earth Science Enterprise demand ever-increasing data rate and storage capability.

- Semiconductor memory for secondary storage is large, consumes power and is expensive.

- Volumetric storage offers lower cost, an order of magnitude smaller size and mass.

- Practical effective surface densities exceed 1Tb/in^2.

- Highly leveraged from efforts at University of Arizona and Call-Recall, Inc., with 2-photon volumetric media.
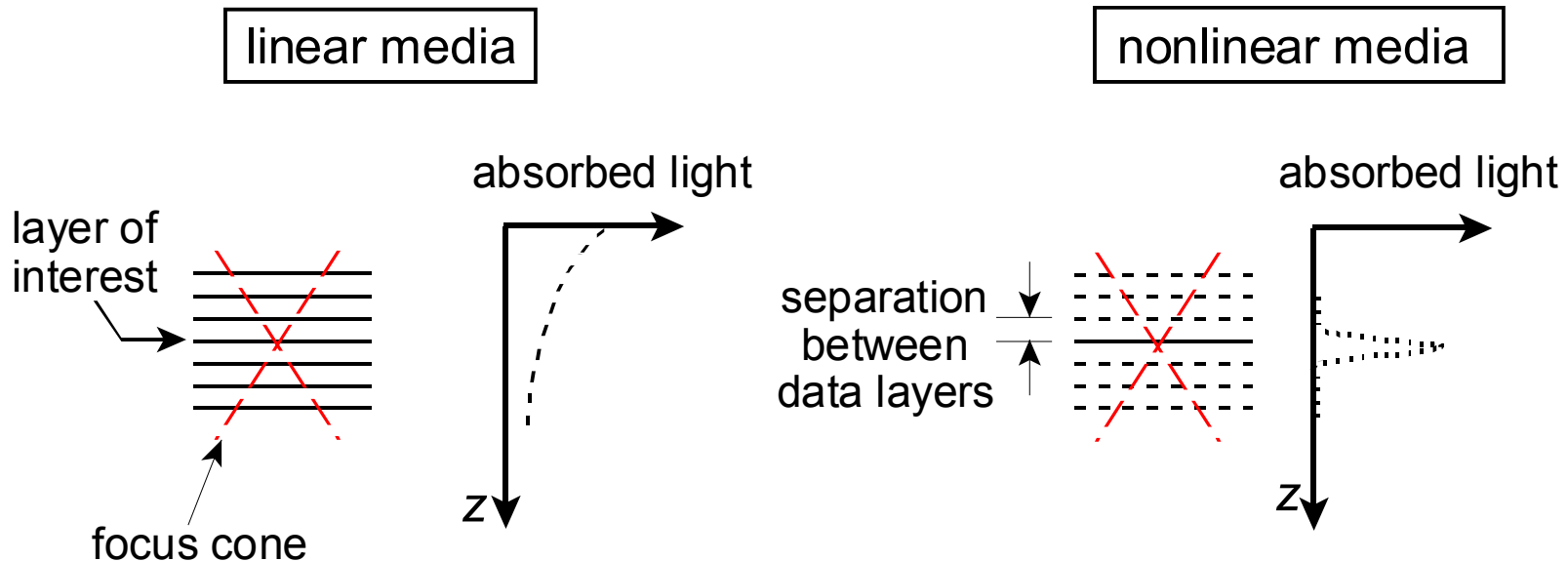
Outline

- Introduction

- Call/Recall, Inc., Media

- Media Characterization in a Simulated Space Environment

- Servo and Prototype Test Stand Development
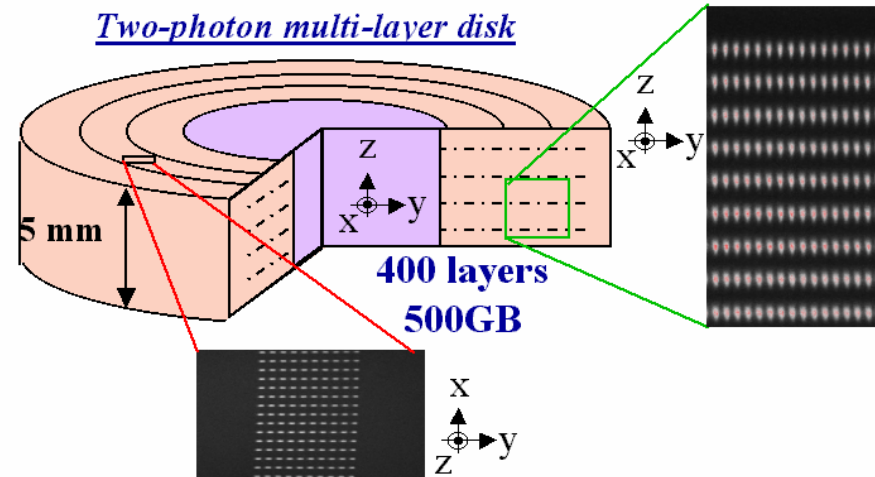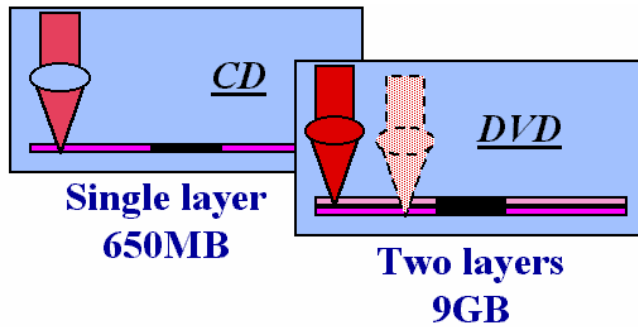
- Summary/Conclusions

- Future Work

Team Members

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- Edwin P. Walker, Scientist (Call/Recall, Inc.)
- Tom Milster, PI (U of AZ)
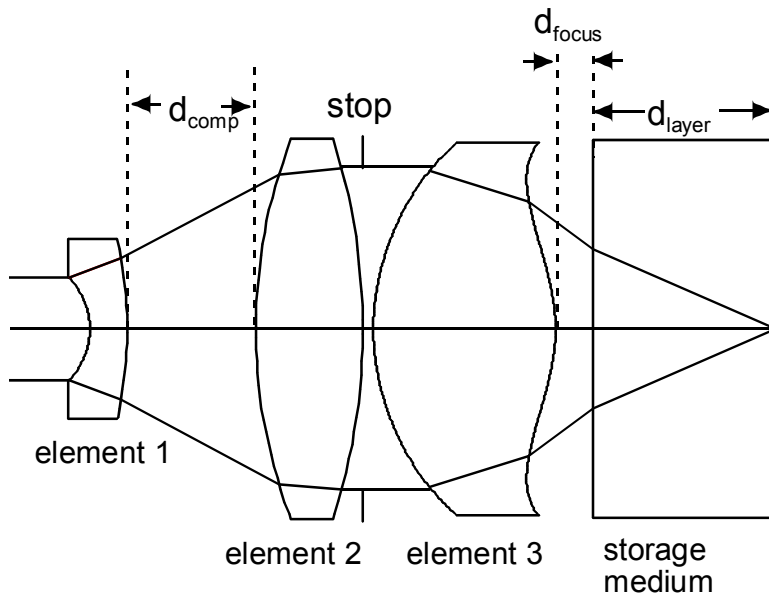
Two-Photon Nonlinear Media Absorption

linear media

nonlinear media

layer of interest

absorbed light

focus cone

separation between data layers

absorbed light

z

z

- Nonlinear absorption characteristics can be used effectively with volumetric memories to isolate a layer of interest.
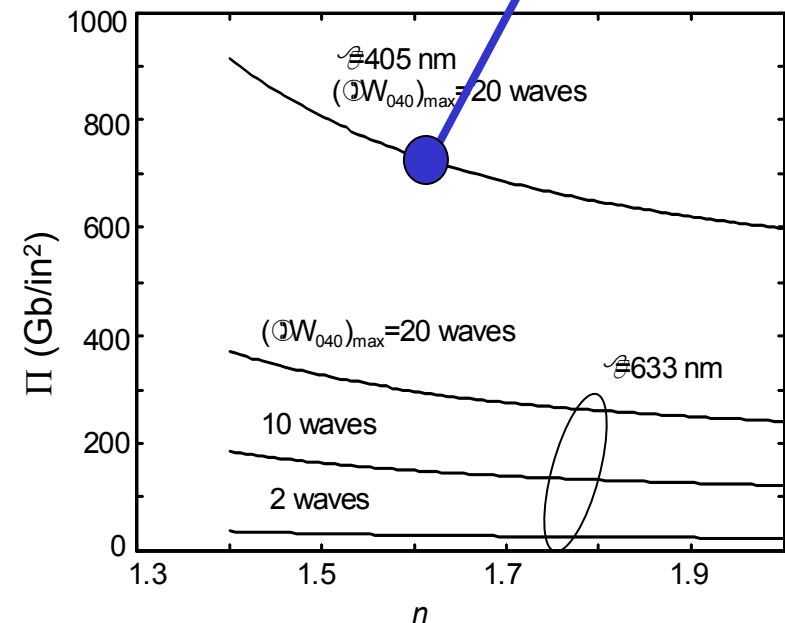
Media Format

Single layer
650MB

Two layers
9GB

Two-photon multi-layer disk

5 mm

400 layers
500GB

What is the *Practical* Expectation for Storage Density?

Far-Field System

1 LOC* = 16 disks

d_{focus}

d_{comp} stop d_{layer}

element 1

element 2   element 3   storage medium

1000

800

600

Π (Gb/in^2)

400

200

0

λ=405 nm
$(\Delta W_{040})_{max}$=20 waves

$(\Delta W_{040})_{max}$=20 waves

λ=633 nm
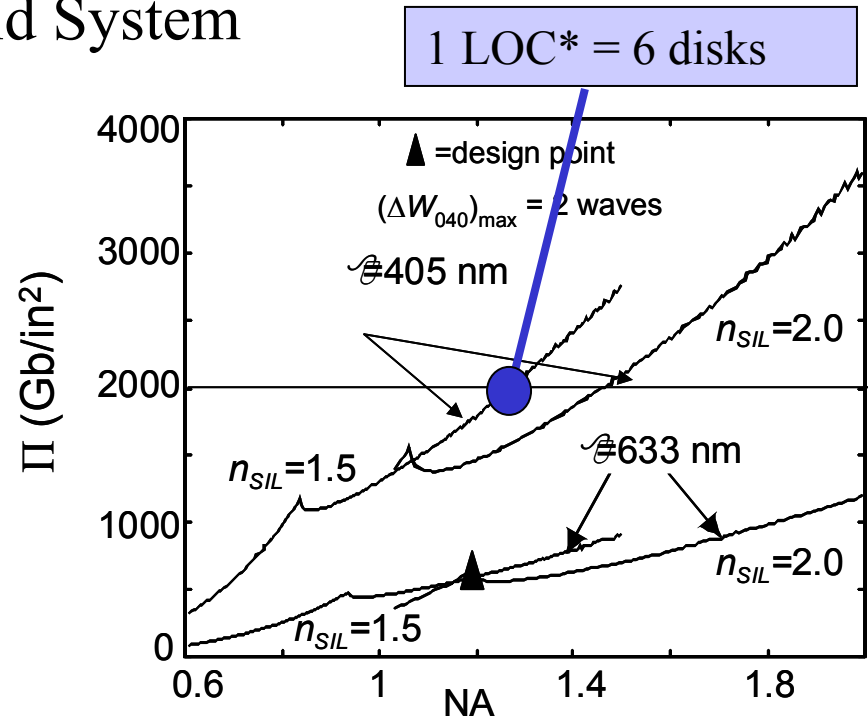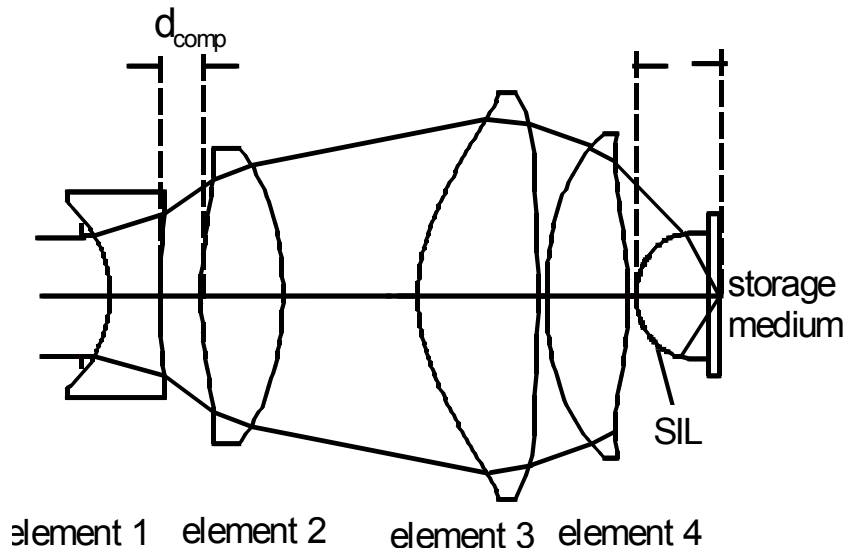
10 waves

2 waves

1.3   1.5   1.7   1.9

n

- Far-field optics

* 1 Library of Congress (LOC) = 20 TB

(Text data as of Y 2000)

- Π = effective surface density (bits/unit area)

- *n* = storage refractive index

- ΔW = aberration compensation

7
Introduction

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What is the *Practical* Expectation for Storage Density?

Near-Field System

1 LOC* = 6 disks

d_{comp}

storage medium

SIL

element 1   element 2   element 3   element 4

=design point

$(\Delta W_{040})_{max}$ = 2 waves

λ=405 nm

n_{SIL}=2.0

n_{SIL}=1.5

λ=633 nm

n_{SIL}=2.0

n_{SIL}=1.5

Π (Gb/in²)

NA
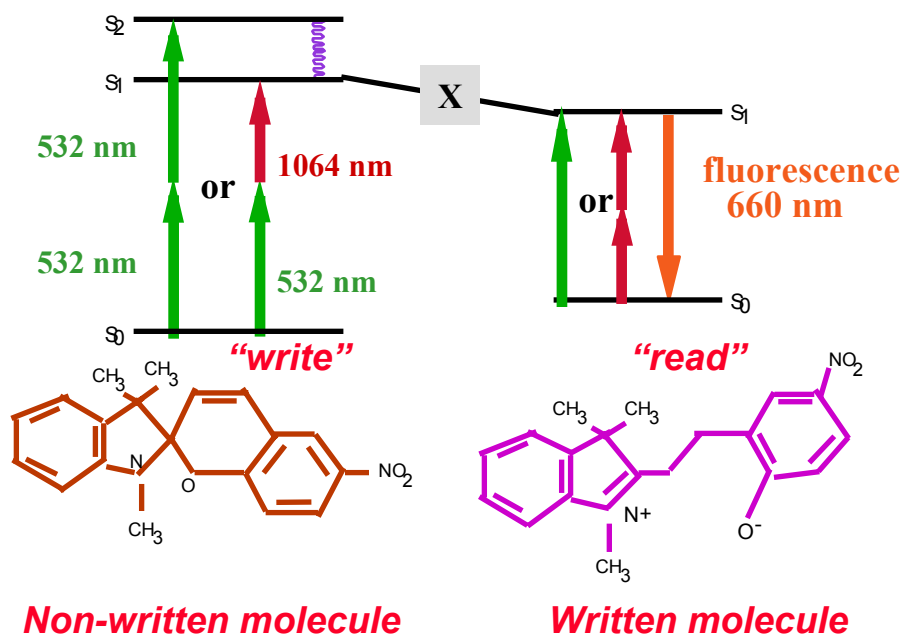
- Near-field optics, NA = 1.2

* 1 Library of Congress (LOC) = 20 TB

(Text data as of Y 2000)

- Π = effective surface density (bits/unit area)
- n = storage refractive index
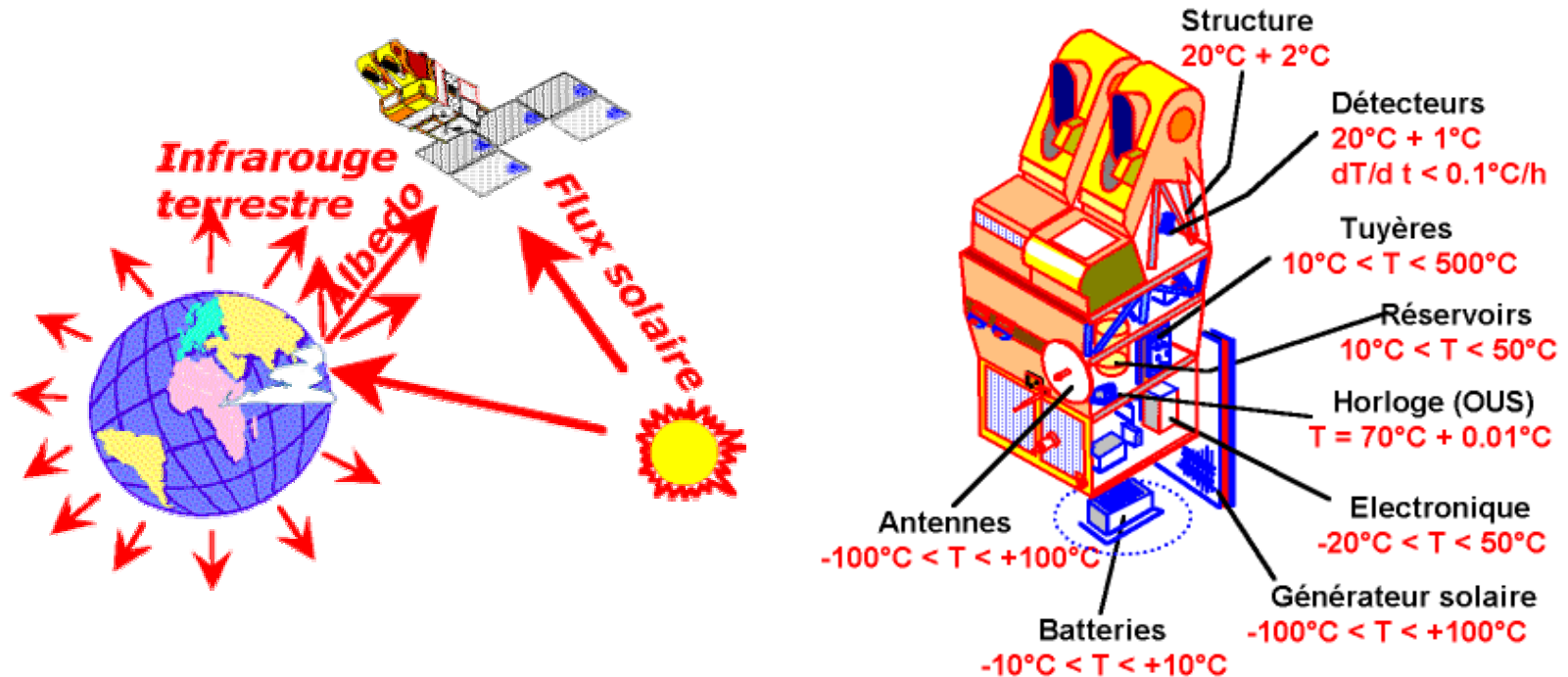- ΔW = aberration compensation

Call/Recall Two-Photon Media Characteristics

Non-written molecule
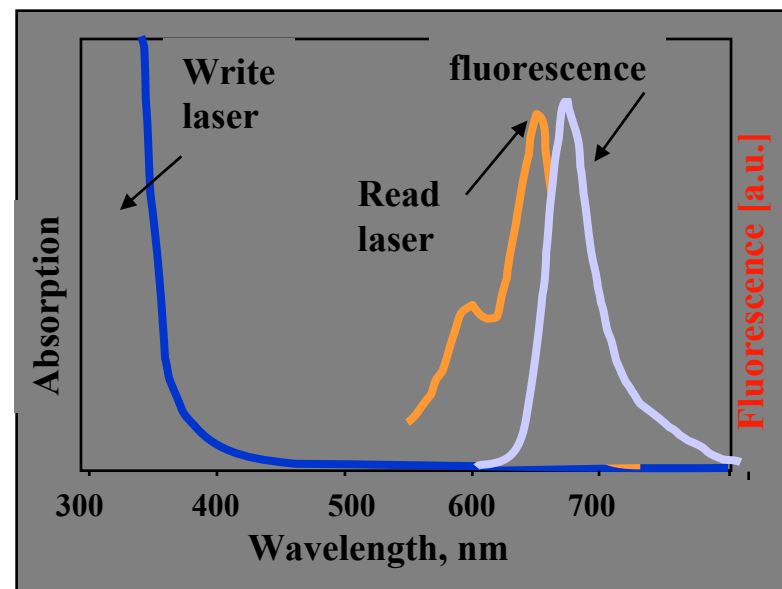
Written molecule

- Energy bands of the written and unwritten molecule result in different absorption and emission characteristics.

- A two-photon process is used for writing.

Media Characterization

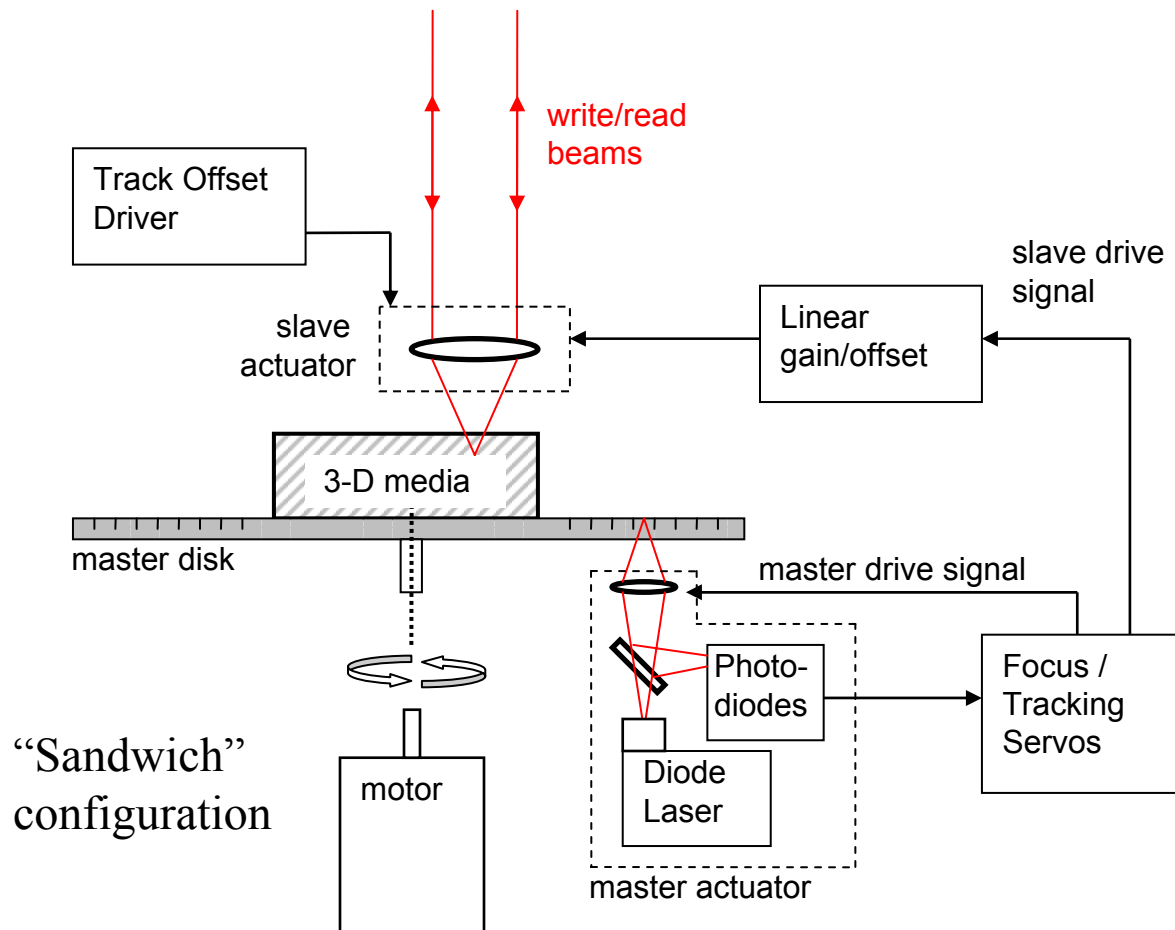## Requirements Similar to Spot 4 Satellite

- Thermal: [-20 C to +50 C (Test to + 90 C)] Surface deformation causes servo errors

- Proton Radiation*: [30 MeV – 60 MeV] Media exposure at 10,000 krad

- Heavy Ion Radiation*: [150 MeV – 350 MeV to 224 krad] Not sensitive

  * Conditions derived from memory chip testing requirements (NASA and others).

Lessons Learned from Media Characterization

- A more robust servo is necessary to help compensate for surface deformations in high-temperature environments.

- More robust media is desirable.

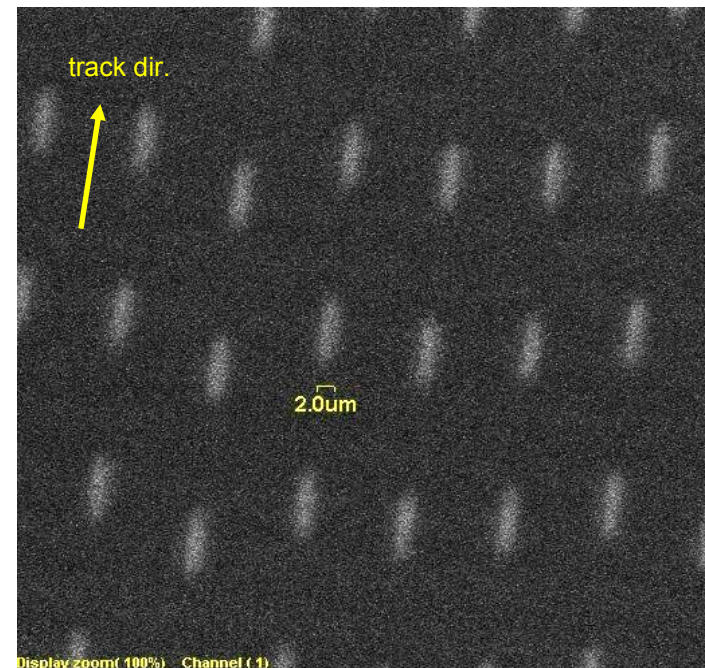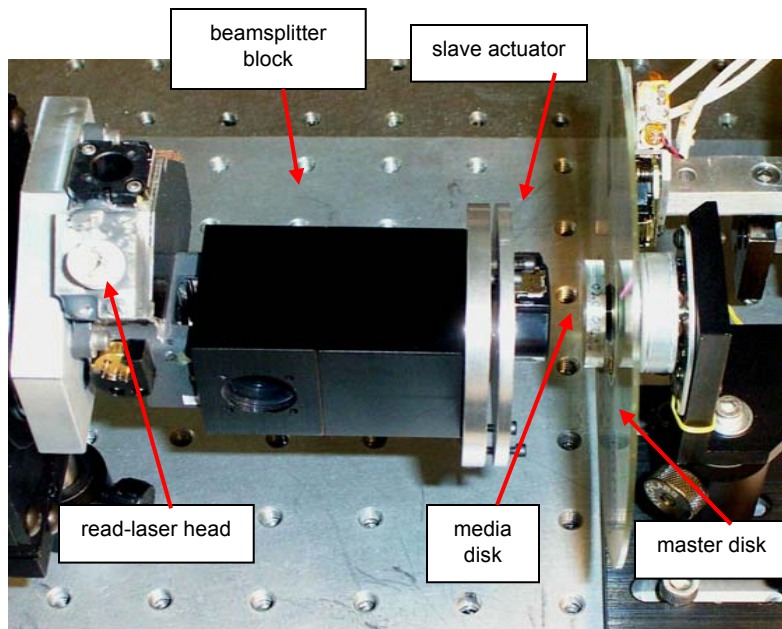# Slave-Servo Concept For Improving Tracking in High-Stress Environments

write/read beams

Track Offset Driver

slave drive signal

slave actuator

Linear gain/offset

3-D media

master disk

master drive signal

"Sandwich" configuration

motor

Photo-diodes

Focus / Tracking Servos

Diode Laser

master actuator

• Master reference features are permanently attached to the volumetric medium.

• Reference signals are derived from the master tracks to control the master and slave actuators.
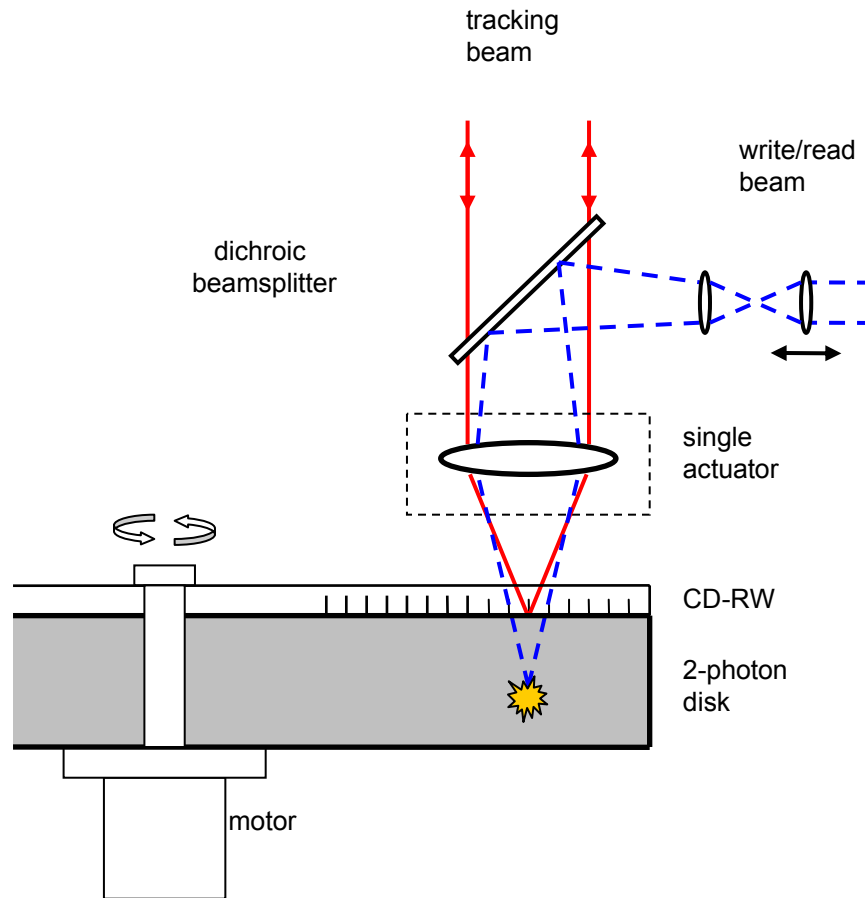
• Many configurations are possible.

12

Sandwich Configuration Prototype Results

Multiple bit tracks are written reliably in volumetric media using a sandwich configuration, at controlled depths and radii inside the media volume.

Long-term instability prevents being able to follow a written track well enough to read bits consistently.


beamsplitter block

slave actuator

read-laser head

media disk

master disk

track dir.

2.0um

Display zoom(100%)   Channel (1)

2-in-1 Configuration

tracking beam

write/read beam

dichroic beamsplitter

single actuator

CD-RW

2-photon disk

motor

• Single actuator design eliminates slave-beam open-loop problems found in other configurations.

• Multiple-wavelengths through single objective lens

• More complicated optics

• Require diffractive optical element (DOE) achromatic compensator.

14

2-in-1 Test Stand Features

- A compact Q-switched writing laser in a TO-3 package that outputs 3kW peak power.

- Commercial diode laser readout integrated into a beam collimating package.

- Integrated laser/detector package for tracking.
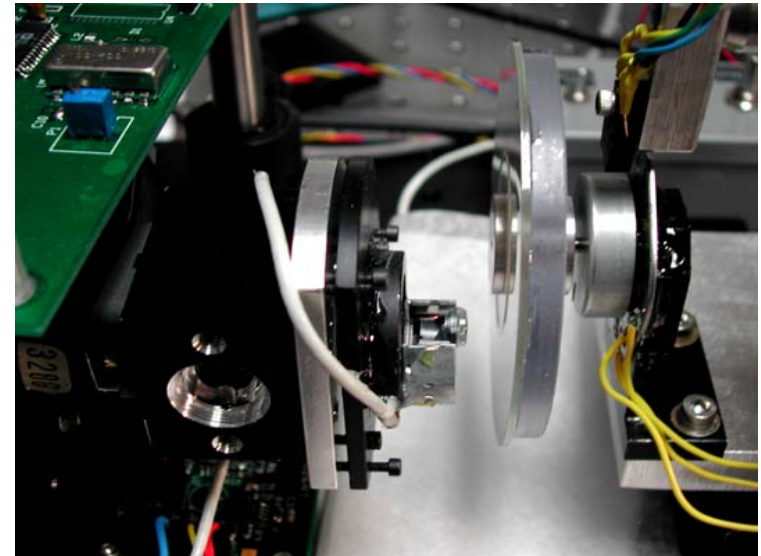
Summary/Conclusions

- Over 1 Tb/in^2 effective surface density is practical with bit-wise volumetric recording.

- Plastic media exhibits degradation in high temperature environments.

- Improved servo systems show promise to realize volumetric potential for space applications.

Future Work

- Next iteration 2-in-1 test stand.

- Analyze ruggedized media and new nonlinear media types.
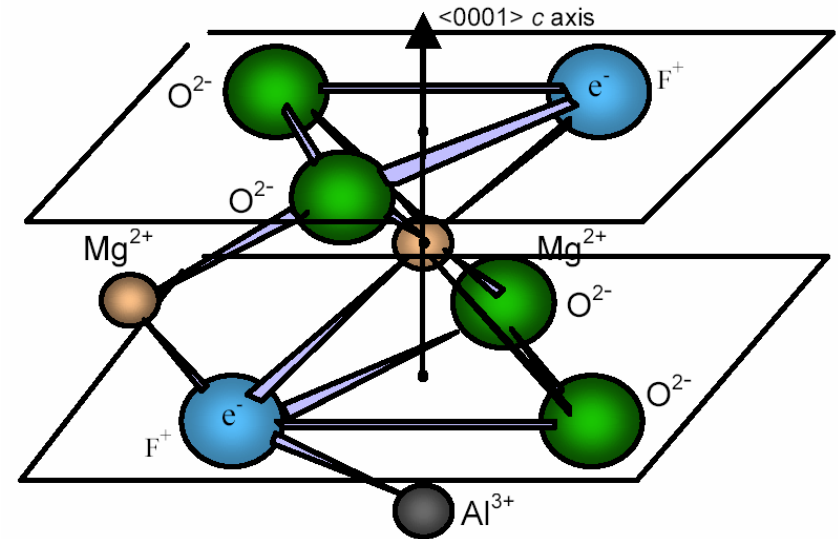
- Wavelength multiplexing to increase data rate.

17

Next 2-in-1 Iteration
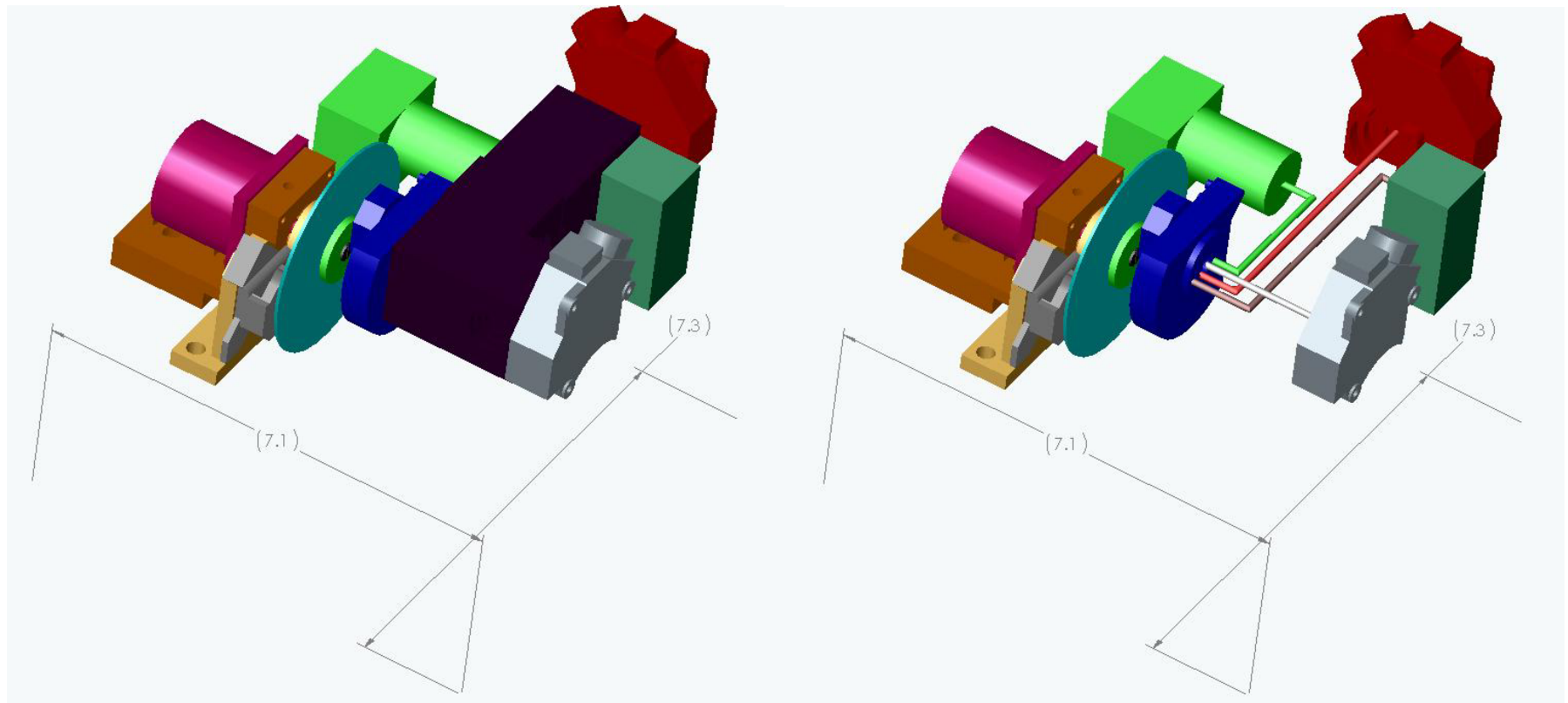
- Smaller form factor

- Bulk off-the shelf components

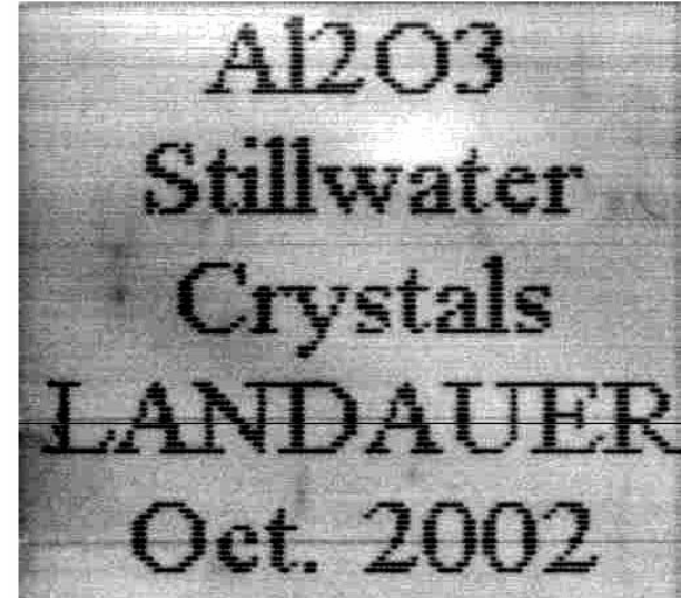# Improved Media
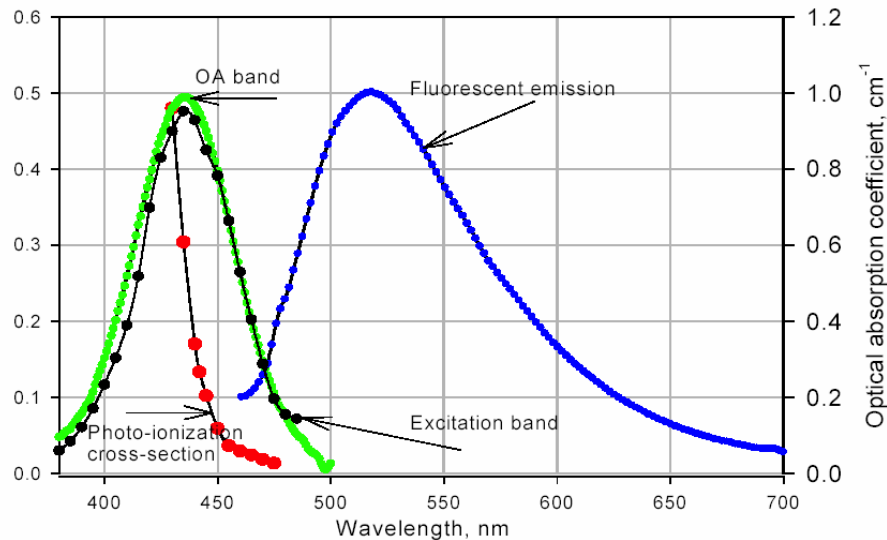
(Possible 2-Photon Media from Landauer*)

- Sapphire-base crystal with impurities to create trapping centers for absorption and subsequent fluorescence.

- Sapphire crystalline structure exhibits many positive mechanical characteristics

*Presented at ODS '03 in Vancouver

Improved Media
(Landauer 2-Photon Media)

- Energy-band structure contains an intermediate level in the absorption band that reduces power requirement on writing.

- Media can be written and read out with commercially-available diodes.

- The media are erasable.

- Disk surface should not be sensitive to temperature effects.
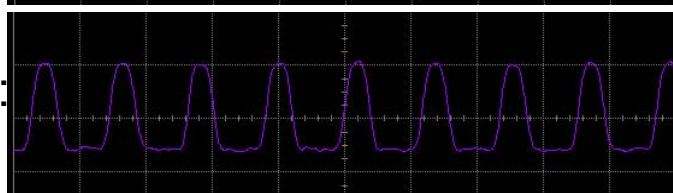
Improved Media
(AgOx Nonlinear Materials*)

Recorded marks on 1st layer
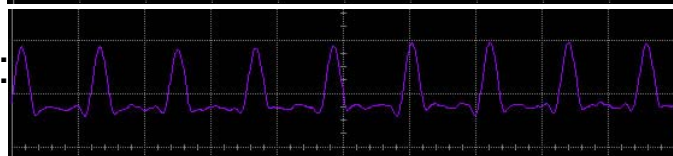(observed by optical microscope)

Writing power: 1.5 mW
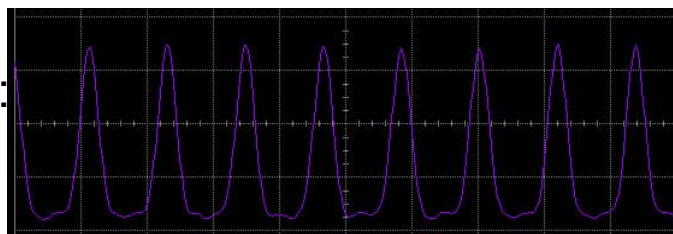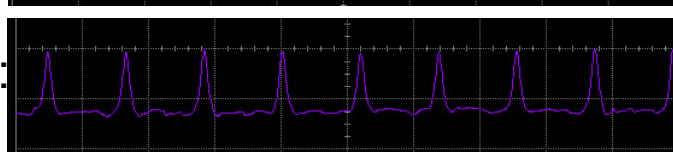
Readout signal form 1st layer

Writing power: 2.5 mW

Readout signal from 2nd layer
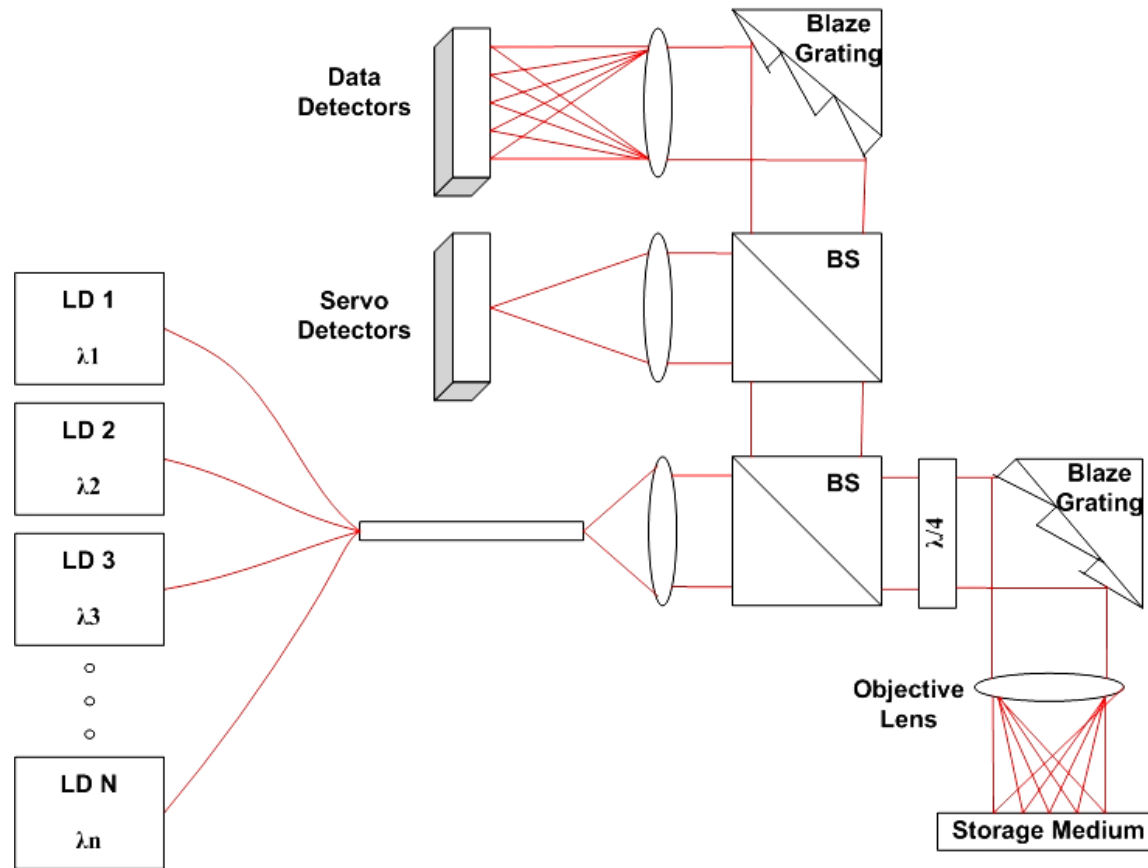
Writing power: 4.2 mW

Readout signal from 3rd layer
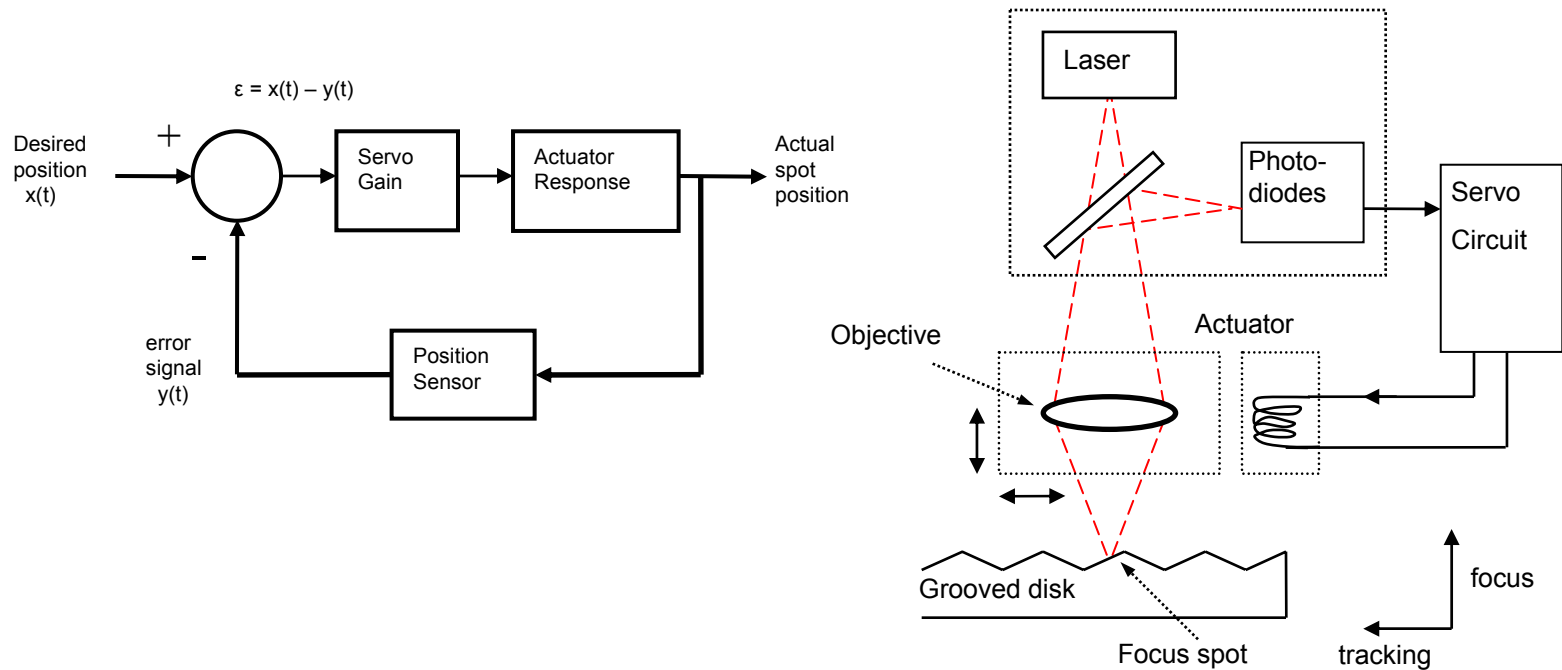
Writing power: 7 mW

Readout signal from 4th layer

*Presented at ODS '03 in Vancouver

Wavelength-Domain Multiplexing

- Laser beams are multiplexed in wavelength in order to increase data rate.

- Each beam focuses to a separate spot on the recording layer of interest.

- Conjugate readout occurs at the detectors.

Servo Basics

$\varepsilon = x(t) - y(t)$

Desired position $x(t)$

Servo Gain

Actuator Response

Actual spot position

error signal $y(t)$

Position Sensor

Laser

Photo-diodes

Servo Circuit

Objective

Actuator

Grooved disk

Focus spot

focus

tracking

- Conventional optical disk systems use closed-loop feedback systems based on disk reference features (tracks) to accurately control spot position on the surface.

- Homogeneous volumetric media have no such reference features.

2-in-1 Initial Layout